

# Tracing the evolution of nearby early-type galaxies in low density environments. The Ultraviolet view from *GALEX*

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**Abstract** We detected recent star formation in nearby early-type galaxies located in low density environments, with *GALEX* Ultraviolet (UV) imaging. Signatures of star formation may be present in the nucleus and in outer rings/arm like structures. Our study suggests that such star formation may be induced by different triggering mechanisms, such as the inner secular evolution driven by bars, and minor accretion phenomena. We investigate the nature of the (FUV-NUV) color vs.  $Mg_2$  correlation, and suggest that it relates to “downsizing” in galaxy formation.

**Keywords** Galaxies: elliptical and lenticular, CD; Galaxies: photometry; Galaxies: fundamental parameters; Galaxies: formation; Galaxies: evolution

## 1 Introduction

Although early-type galaxies (ETGs hereafter) are considered the fossil record of the process of galaxy evo-

lution, there is growing evidence that “rejuvenation” episodes may occur in their star formation history. In this context, the halo mass of ETGs is the main driver for their evolution, however also the environment plays a significant role (Clemens et al. 2006, 2009). According to these studies, the galactic nuclei (SDSS fibers sample the central  $3''$ ) of ETGs in low density environments (LDE hereafter) are about 20% younger than those of their cluster counterparts. Wide-field (1.25 degrees diameter), deep far-UV (1344 – 1786 Å) and near UV (1771 – 2831 Å) imaging from *GALEX* (see for details Bianchi these proceedings) is greatly contributing to this view. Using *GALEX* data, e.g. Schawinski et al. (2007) found that 30% of massive ETGs show ongoing star formation, and that this fraction is higher in LDE than in the high-density environments.

Rampazzo et al. (2007) and Marino et al. (2009) showed that ETGs with shell structures (indicative, according to simulations, of recent accretion episodes) host a “rejuvenated” nucleus (see also Longhetti et al. 2000, for optical spectroscopic studies). Similar results have been obtained by Jeong et al. (2009) for the SAURON galaxy sample (de Zeeuw et al. 2002).

We are performing a comprehensive, multi wavelength study of 65 nearby ETGs, a large fraction of which show ionized gas emission, predominantly located in LDE (Annibali et al. 2007, 2010, A07 and A10 hereafter). The sample is composed of 70% of elliptical and 30% of S0s (see both de Vaucouleurs et al. 1991; Sandage & Tammann 1987). Anyway, from the kinematic point of view, about 68% of our ETGs have fast rotator characteristics in the  $\epsilon$  vs.  $V/\sigma_e$  plane (see Appendix A in A10).

Here we present the *GALEX* view for a sub-sample of 40 ETGs, out of the 65 in the original sample, available in the NASA archive. The UV spectral region is sensitive to even small amounts of recent star formation, and is thus effective in unveiling possible “rejuvenation”

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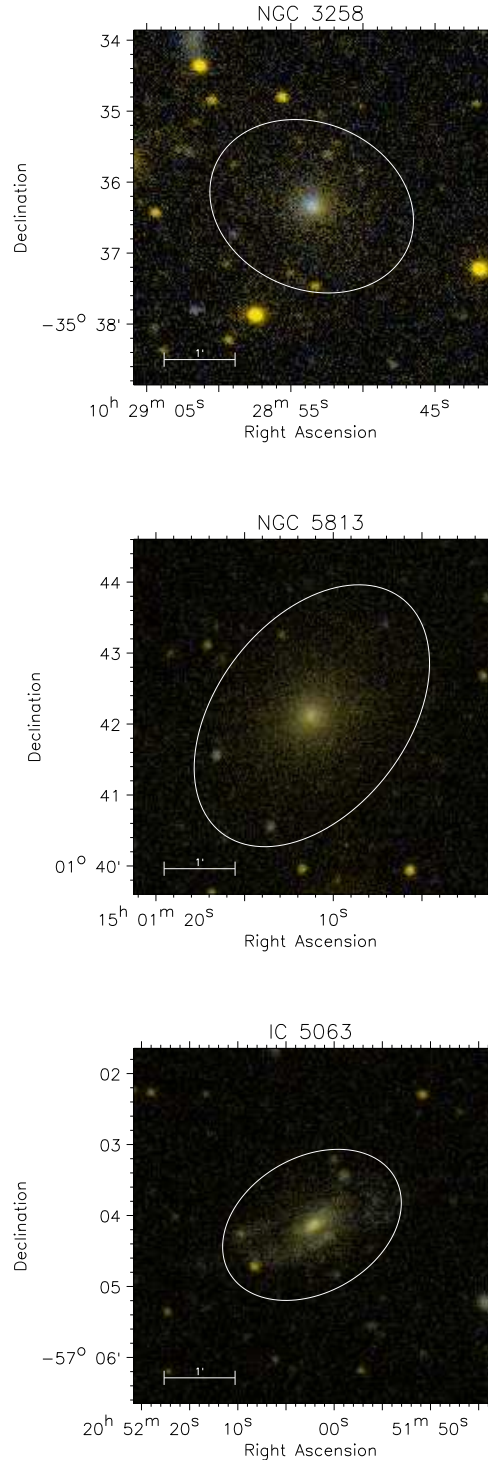
episodes. For a detailed presentation of the GALEX FUV and NUV photometry we refer to Marino et al. (2010). We review our multi-wavelength approach in quest of signatures of recent star formation in ETGs. Finally we combine the analysis of the UV photometry with optical line-strength indices and show preliminary results.

## 2 Looking for signatures of recent star formation: a multi-wavelength sweep

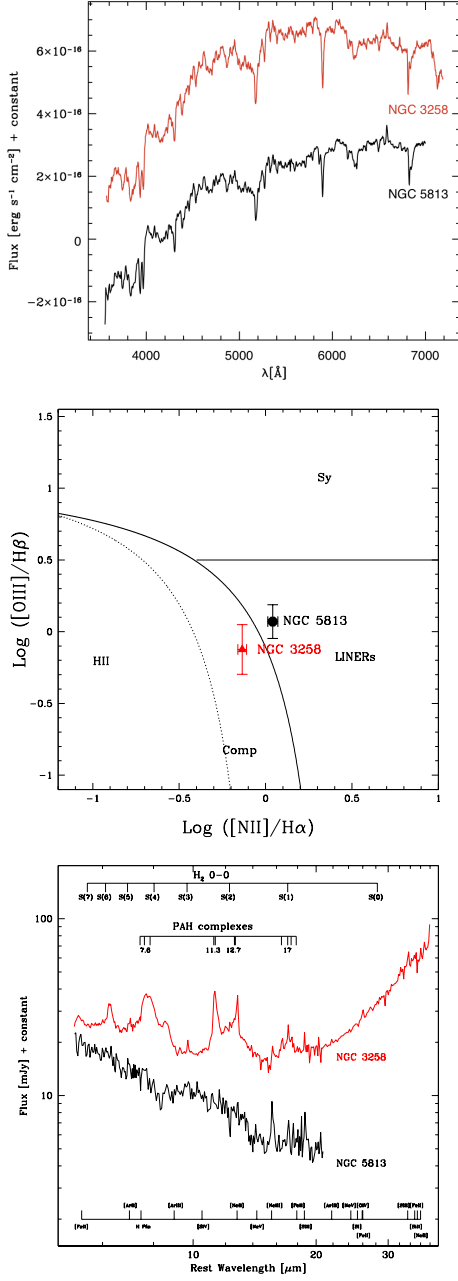
In Figure 1 we show the composite *GALEX* image of three ETGs in the Marino et al. (2010) sample, NGC 3258, NGC 5813 and IC 5063.

Notwithstanding the unperturbed morphology revealed by both the deep optical (Tal et al. 2009) and our UV imaging, NGC 3258 and NGC 5813 hide a different recent star formation history. The analysis of the optical line-strength indices performed by A07 shows that NGC 3258 has a “young” average stellar population (luminosity-weighted age of  $4.5 \pm 0.8$  Gyr). At odds, NGC 5813 is a relatively old ETG ( $11.7 \pm 1.6$  Gyr). The nuclear optical spectra of these galaxies are shown in the top panel of Figure 2. Like the imaging, their spectra do not show peculiarities: emission lines are, indeed, found in a relatively large fraction of ETGs (between 45% to 80% depending on the sample analyzed in the literature, see e.g. the review in A10). The classic  $[\text{NII}](\lambda 6584)/\text{H}\alpha$  vs.  $[\text{OIII}](\lambda 5007)/\text{H}\beta$  diagnostic diagram (Baldwin et al. 1981, BPT diagram) is shown in the mid panel of Figure 2. The diagram shows that the two galaxies host a LINER/Composite nucleus (A10) as large fraction of ETGs (see e.g. Phillips et al. 1986; Sarzi et al. 2006).

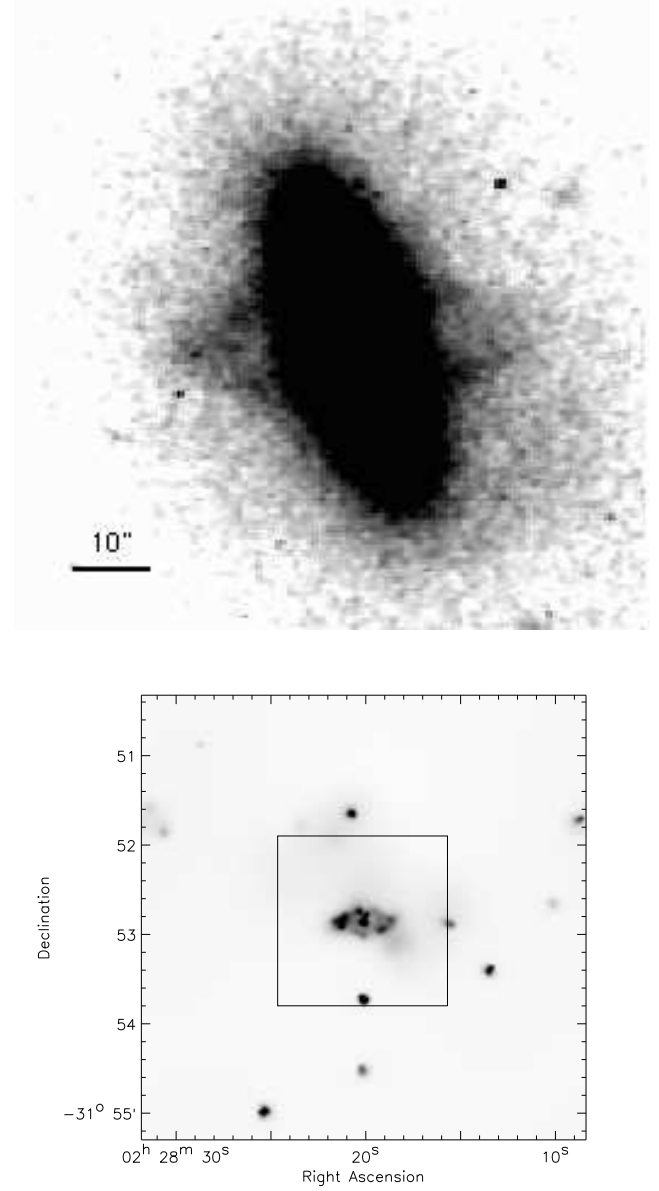
The different star formation history suggested by the optical results is supported by our *Spitzer* mid-infrared (MIR) observations (Panuzzo et al. 2010). Despite the remarkable similarity of the shape of their optical spectra, the nuclear MIR emission of NGC 3258 and NGC 5813, shown in the bottom panel of Figure 1, is completely different. The Polycyclic Aromatic Hydrocarbons emission (PAH) complexes at  $6.2 \mu\text{m}$ ,  $7.7 \mu\text{m}$ ,  $11.3 \mu\text{m}$  and  $17 \mu\text{m}$  dominate the MIR spectrum of NGC 3258. Their ratios indicate that the galaxy nucleus has undergone a recent starburst (see details in Panuzzo et al. 2010; Vega et al. 2010). At odds, the MIR spectrum of NGC 5813 displays a broad emission feature around  $10 \mu\text{m}$  attributed to the silicate emission arising from dusty circum-stellar envelopes of O-rich AGB stars, superimposed on the photospheric stellar continuum from red giant stars. This is the typical spectrum of passively evolving ETGs (see e.g. Bressan et al. 2006).



**Fig. 1** GALEX false color image (FUV blue; NUV yellow) of NGC 3258, NGC 5813 and of the Seyfert 2 IC 5063 (adapted from Marino et al. (2010)). The ellipse marks the isophote at  $\mu_B = 25 \text{ mag arcsec}^{-2}$  ( $D_{25}$ ). Optical line-strength indices indicate that NGC 3258 has a luminosity weighted age of  $4.5 \pm 0.8$  Gyr, while NGC 5813 is an old ETG with an age of  $11.7 \pm 1.6$  (see Annibali et al. 2007)



**Fig. 2** Optical (see details in Rampazzo et al. 2005; Annibali et al. 2006) and MIR spectra of NGC 3258 and NGC 5813 galaxies imaged in Figure 1. The top panel shows the nuclear spectra of the two galaxies, fluxes are shifted arbitrarily, in the range  $3750 \leq \lambda \leq 7250 \text{ \AA}$ . In the mid panel we show the position of the two galaxies in the typical BTP diagram (see for details A10) which indicates the LINER/Composite nature of the two galaxy nuclei. The bottom panel shows the *Spitzer*-IRS MIR spectra. Notice the presence of PAHs in the spectrum of NGC 3258 at odds with NGC 5813. A cold dust component is also visible in the NGC 3258 spectrum



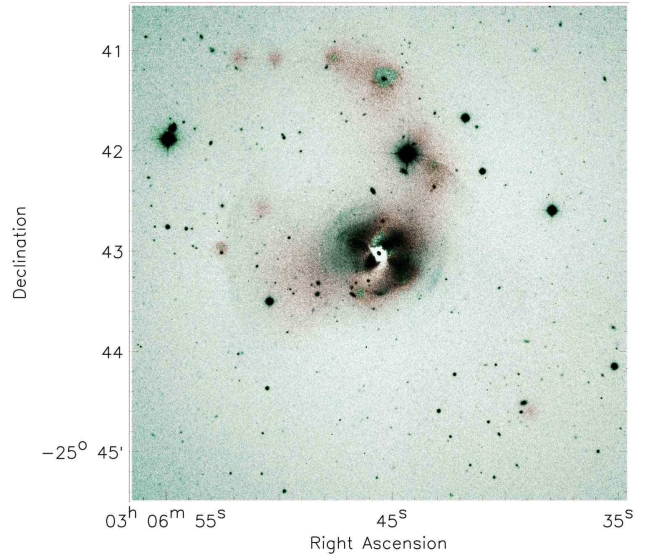
**Fig. 3** B-band (top panel) and *GALEX* FUV images (bottom panel) of MCG-05-07-001, a southern polar ring galaxy. In the FUV band (the square encloses the field of view of the B-band image), only the ring and the nucleus of the galaxy are visible: the old main body of the galaxy disappears (see Marino et al. 2009, for details)

IC 5063, at the bottom of Figure 1, is a well known Seyfert 2 (see Veron & Veron 2006). It was the first galaxy in which a fast neutral hydrogen outflow was discovered (see Morganti et al. 2007, and reference therein). Morganti et al. have also found evidence of cold and warm gas outflows and noticed that the outflow rate, associated to the HI, is in the same range as for “mild” starburst driven superwinds in ULIRGs. Although limited to the inner kpc region the observed outflows may have sufficient kinetic power to have a significant impact on the evolution of the interstellar medium of IC 5063. In A10 we show that in IC 5063 a Seyfert like ionization extends out to our largest sample radius,  $r_e/2$ , i.e. about 3 kpc ( $H_0=75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ). In general in A10 we show that a link exists between the AGN phenomenon and the presence of recent star formation in the galaxy nucleus. With the *GALEX* imaging we extend our search for star formation to the galaxy outskirts. Figure 1 shows the complex, outer, blue ring-like structure detected in UV in IC 5063. The origin of such structure may be connected with an accretion episode as the complex dust-lane crossing the galaxy.

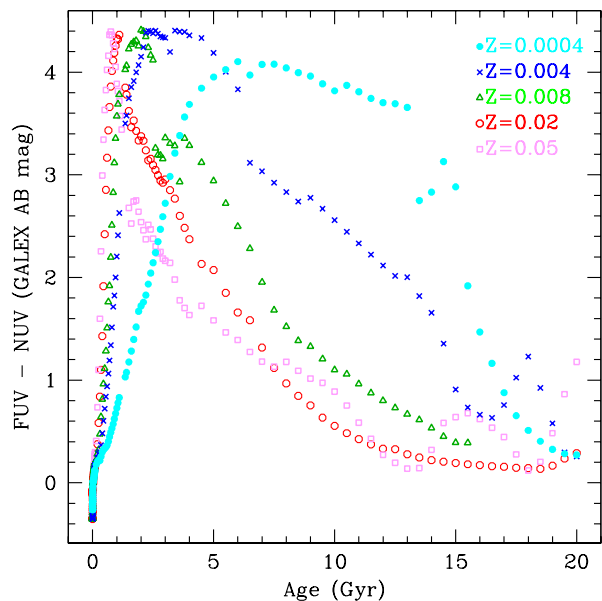
In our sample, four barred S0 galaxies, namely NGC 1533, NGC 2962, NGC 2974 and NGC 3489, show outer blue ring/arm-like structures. The recent star formation detected in this kind of rings is discussed in the Marino et al. paper in this conference proceedings. We emphasize here that such outer ring/arm-like structures are likely due to inner secular evolution of a galaxy driven by the bar (see for a kinematical review Moiseev & Bizyaev 2009). The bar formation may have been induced by a galaxy-galaxy interaction within the groups (see e.g. pioneering simulations of Noguchi 1990).

The rings in the above barred S0s have a different origin from polar rings and/or collisional rings and tidal structures seen in some ETGs where accretion or major merger episodes have recently occurred. In Figure 3 we show an example of a polar-ring galaxy studied in Marino et al. (2009). A very young, lower than 1 Gyr, stellar population is present in the ring and is evidence of a recent accretion/merging phenomenon. ETGs with polar rings in the Local Universe are quite rare: only 0.5% of ETGs show such phenomenon (Whitmore et al. 1990). Rings closely associated with a bar are much more common, they are present in about 20-30% of lenticular and spiral galaxies (Buta & Combes 1996).

Seven ETGs in the Marino et al. (2010) sample show a shell system, namely NGC 1533, NGC 2974, NGC 4552, NGC 6958, NGC 7135, NGC 7192 and IC 1459 (see the compilation of Malin & Carter 1983; Tal et al. 2009). Shells or ripples are revealed in about 15-20%

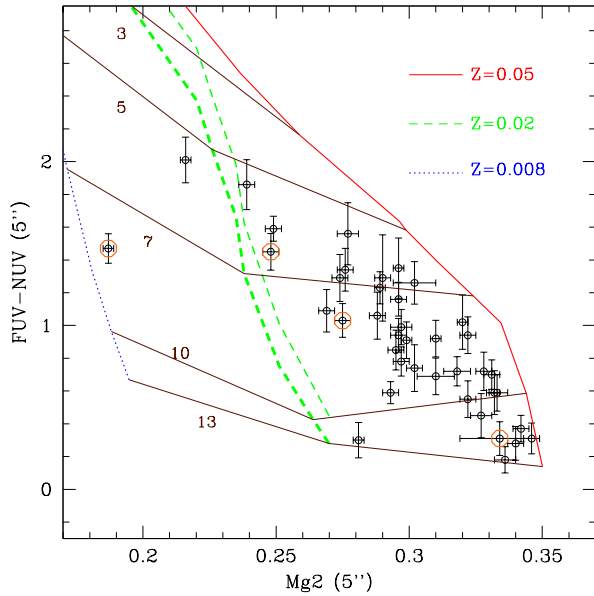


**Fig. 4** The *GALEX* FUV emission (red areas) is superposed to the residual of the optical image of NGC 1210 after the main body of the galaxy has been subtracted. The residuals show a wide system of shells and a complex central fine structure. A ring of HI emission, which perfectly superposes to the *GALEX* FUV, has been detected by Schiminovich et al. (2001) (see Marino et al. 2009, for details)



**Fig. 5** SSP (FUV-NUV) GALEX color in the AB mag system as a function of age, for five metallicity values ( $Z_{\odot}=0.0156$ , Caffau et al. (2009))





**Fig. 6** (FUV–NUV) colors versus the  $Mg_2$  index measured within a  $5''$  radius aperture (Marino et al. 2010). The big circles indicate galaxies classified as Seyferts by Annibali et al. (2010). Overplotted are SSP models for different ages (13, 10, 7, 5 and 3 Gyr) and metallicities ( $Z=0.05$ ,  $0.02$ ,  $0.008$ ), and  $E(B-V)=0$ . The thin dashed line is for a  $Z=0.02$  SSP with  $E(B-V)=0.3$ .

of ETGs (see e.g. Malin & Carter 1983; Reduzzi et al. 1996). The most successful models for explaining shells consider the accretion of a smaller companion by a giant ETG (see e.g. Quinn 1984; Dupraz & Combes 1986; Ebrova et al. 2009). The small galaxy accreted disintegrates in the giant potential and its stars begin to oscillate forming shells. If the accretion is “wet”, stars and gas segregates. The gas dissipates the orbital kinetic energy and falls toward the primary center settling into compact disks or rings in/around the primary nucleus (Weil & Hernquist 1993). NGC 1210 is a beautiful example of shell galaxy. In Figure 4, the *GALEX* FUV flux distribution provides clear evidence for an accretion event. Marino et al. (2009) suggest that also the nucleus of NGC 1210 has been rejuvenated and the accretion episode, that triggered the star formation, should be dated between 2 and 4 Gyr ago.

### 3 The nuclear (FUV-NUV) vs. $Mg_2$ relation

Both the secular galaxy evolution and the accretion driven evolution tend to refuel the galaxy nucleus of fresh gas and trigger star formation.

Complementing UV colors with optical line strength indices is a way to characterize the star formation his-

tory of ETGs, and in particular to unveil the possible presence of secondary star formation events.

Combining *GALEX* photometry with optical line-strength indices, Donas et al. (2007) found a tight anti-correlation between the (FUV–NUV) color and the  $Mg_2$  index for a sample of 130 nearby ETGs (see also Rampazzo et al. 2007), in the sense that the (FUV–NUV) color becomes bluer as the  $Mg_2$  index increases. The same trend appears between the UV color and the galaxy central velocity dispersion. Donas et al. (2007) suggest that these correlations are mainly driven by metallicity and reflect blanketing in the NUV being correlated with the overall metallicity.

To understand how the (FUV–NUV) color is affected by age and metallicity, we computed synthetic magnitudes in the *GALEX* systems for a set Simple Stellar Populations (SSPs) of different ages and metallicities (Bressan, unpublished, see also Clemens et al. (2009); Chavez et al. (2009); Bianchi (2009)). Our results are illustrated in Figure 5.

At the youngest ages, the SSPs have the bluest (FUV–NUV) colors ( $\sim -0.1$  mag for a 10 Myr old population with  $Z=0.02$ ), as the O-type and B-type stars contribute most of the FUV flux; then they become redder as the age increases (up to  $\sim 4.4$  mag). For ages older than 1 to a few Gyrs (depending on metallicity), the trend is inverted, and the (FUV–NUV) color becomes progressively bluer as the age increases ( $\approx 0.3$  mag for a 13 Gyr old population with  $Z=0.02$ ).

This behavior can be understood considering that the NUV band is highly dominated by turnoff stars. On the other hand, the FUV emission of old “normal” stellar populations is dominated by post asymptotic giant branch (PAGB) stars. In younger and more metal poor populations, the turnoff is bluer and more luminous, and emits more in the NUV; at the same time, the contribution to the FUV from PAGB stars diminishes because, in spite of the higher luminosity, the duration of the PAGB phase gets much shorter (i.e., the fuel decreases). This implies that for ages older than 1–5 Gyrs (depending on the metallicity) the (FUV–NUV) color at any given age is redder for lower metallicity. However, the situation could be more complex if “anomalous” sub-populations, such as those suggested to be responsible for the UV-upturn of elliptical galaxies, are present. For populations younger than 1–5 Gyr, the turnoff starts to contribute significantly to the FUV band, and the reddening of the (FUV–NUV) color with age is modulated by metallicity. It follows that, for populations older than  $\sim 1$  to a few Gyrs, bluer (FUV–NUV) colors can be caused by either older ages or larger metallicities.

Our analysis aims at clarifying whether the observed (FUV–NUV) vs  $Mg_2$  (or  $\sigma$ ) is driven by age

or by metallicity (or both). In Figure 6 we show the (FUV–NUV) color measured in the central 5'' of the galaxy versus the  $Mg_2$  index for our sample of 40 ETGs. Superimposed are our SSP models. Lines of constant age run almost horizontal, while lines of constant metallicity are more vertical. Figure 6 shows that the slope of the (FUV–NUV) vs.  $Mg_2$  correlation is significantly steeper than the lines of constant age and it is very close to the slope defined by the models of constant metallicity. This suggests that the (FUV–NUV) vs.  $Mg_2$  trend is driven more by age than by metallicity, with redder ETGs being also younger. In this sense, the (FUV–NUV) vs.  $Mg_2$  anti-correlation is more an aspect of “downsizing” rather than of the color-metallicity relation.

There is a caveat on the above conclusions due to the fact that the plotted models do not account for the effect of  $\alpha$ -enhanced chemical compositions. However, the effect of the  $\alpha$ -enhancement on the  $Mg_2$  index turns out less important than the dependence on the total metallicity. For example, for a 7 Gyr old population, a factor of 2 increase in  $Z$  (+0.3 dex) implies a  $\sim 20\%$  increase in  $Mg_2$  index, while a 0.3 dex increase in  $[\alpha/Fe]$  implies a 7% increase in  $Mg_2$  index. This is because the  $[\alpha/Fe]$  enhancement is mainly due to an iron depletion rather than to an Mg enhancement. On the other hand, we cannot quantify with the present models the effect of the  $[\alpha/Fe]$  enhancement on the UV colors.

The possible contribution of “anomalous” sub-populations, such as those suggested to be responsible for the UV-upturn of elliptical galaxies, and the  $[\alpha/Fe]$  enhancement on the UV colors will be the subject of a forthcoming paper.

New UV observational facilities, like the WSO-UV observatory (Shustov et al. 2009, 2011), will be crucial to fully understand the evolution of ETGs.

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